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Benson et al.

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(45) **Date of Patent: Sep. 8, 2015**

(54) **ELECTRIC MOTOR PHASE CONTROL SYSTEM**

(71) Applicant: **The Boeing Company**, Chicago, IL (US)

(72) Inventors: **Christopher Pete Benson**, Berkeley, CA (US); **Douglas C. Cameron**, Ladera Ranch, CA (US)

(73) Assignee: **THE BOEING COMPANY**, Chicago, IL (US)

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H02P 6/18 (2006.01)

(52) **U.S. Cl.**
CPC ***H02P 6/182*** (2013.01)

(58) **Field of Classification Search**
USPC 318/445, 452, 459, 400.13, 400.14, 318/400.17, 62, 400.03, 778, 264, 2, 72, 318/277
See application file for complete search history.

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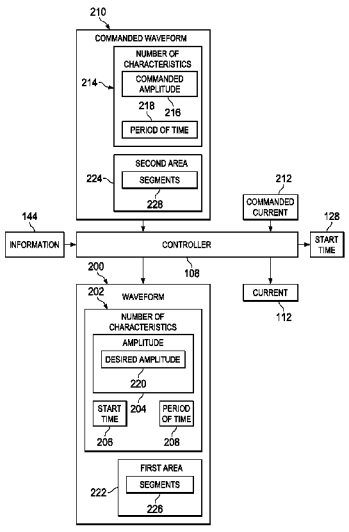
Primary Examiner — Kawing Chan
Assistant Examiner — Jorge L Carrasquillo
(74) *Attorney, Agent, or Firm* — Yee & Associates, P.C.

(57) **ABSTRACT**

A method and apparatus for controlling an electric motor. A controller is configured to identify a start time for a signal based on a back electromotive force present in an electric motor during operation of the electric motor. The start time is for a position of a rotor relative to a group of coils. The controller is further configured to send the signal to the group of coils using the start time identified. An effect of the back electromotive force on the signal is reduced.

16 Claims, 9 Drawing Sheets



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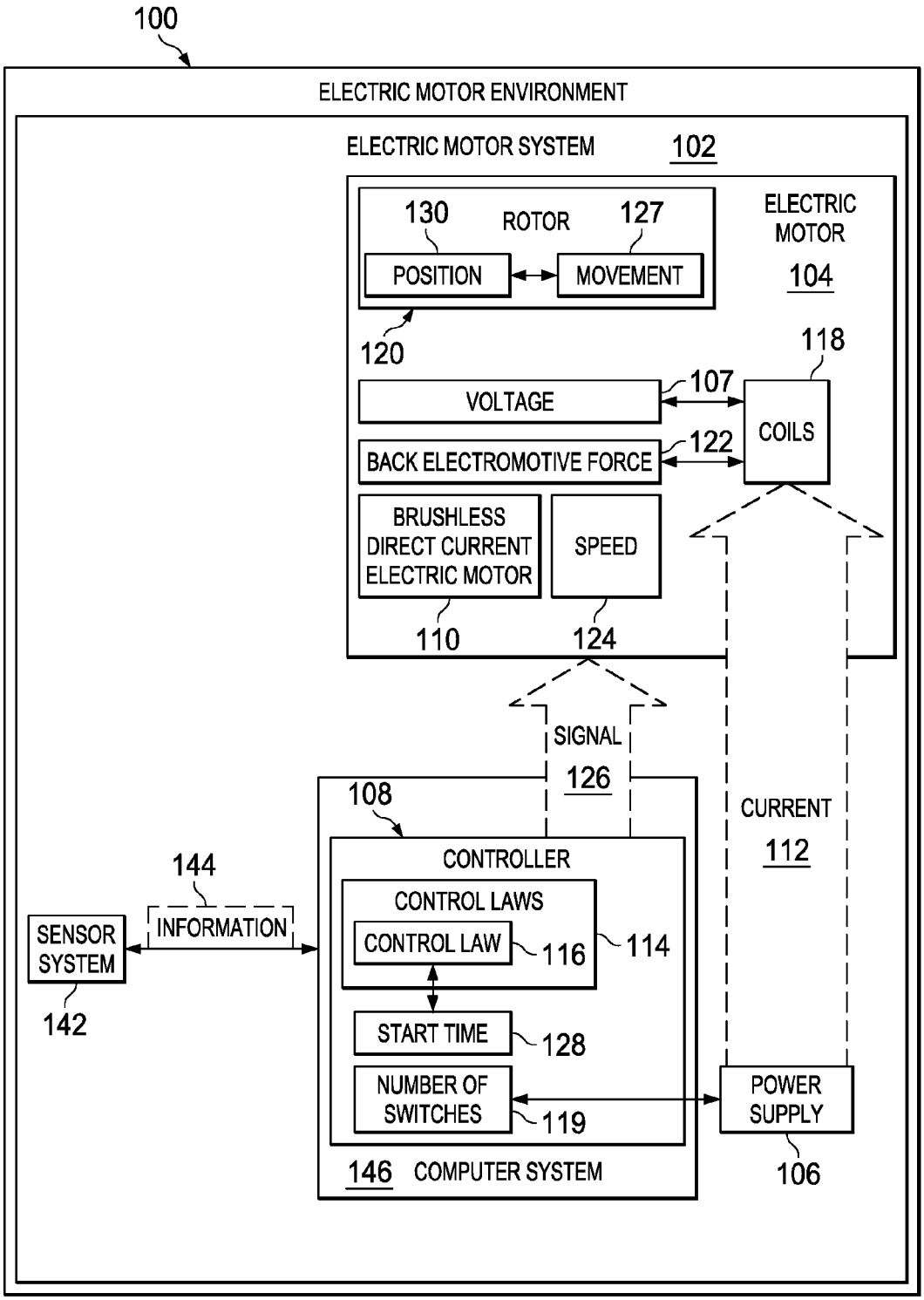

100
ELECTRIC MOTOR ENVIRONMENT
ELECTRIC MOTOR SYSTEM 102
130
ROTOR
127
POSITION
MOVEMENT
ELECTRIC MOTOR 104
120
118
VOLTAGE
107
COILS
BACK ELECTROMOTIVE FORCE
122
BRUSHLESS DIRECT CURRENT ELECTRIC MOTOR
SPEED
110
124
SIGNAL 126
CURRENT 112
108
CONTROLLER
144
CONTROL LAWS
SENSOR SYSTEM
INFORMATION
CONTROL LAW
116
114
142
START TIME
128
NUMBER OF SWITCHES
119
POWER SUPPLY
106
146 COMPUTER SYSTEM

FIG. 1

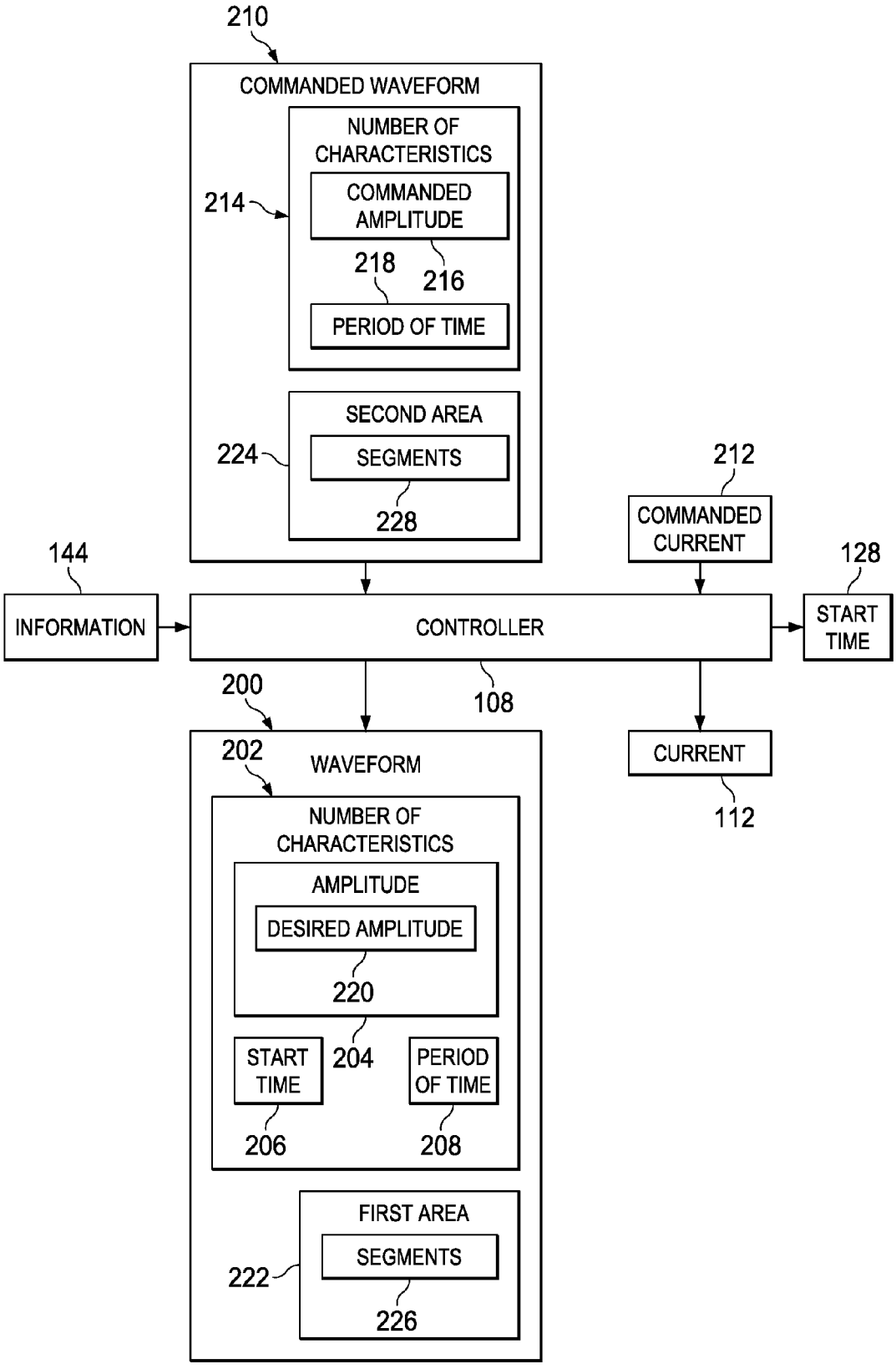

210
COMMANDED WAVEFORM
NUMBER OF CHARACTERISTICS
214
COMMANDED AMPLITUDE
218
216
PERIOD OF TIME
SECOND AREA
224
SEGMENTS
228
212
COMMANDED CURRENT
144
128
INFORMATION
CONTROLLER
START TIME
200
108
202
WAVEFORM
CURRENT
112
NUMBER OF CHARACTERISTICS
AMPLITUDE
DESIRED AMPLITUDE
220
START TIME
204
PERIOD OF TIME
206
208
FIRST AREA
222
SEGMENTS
226

FIG. 2

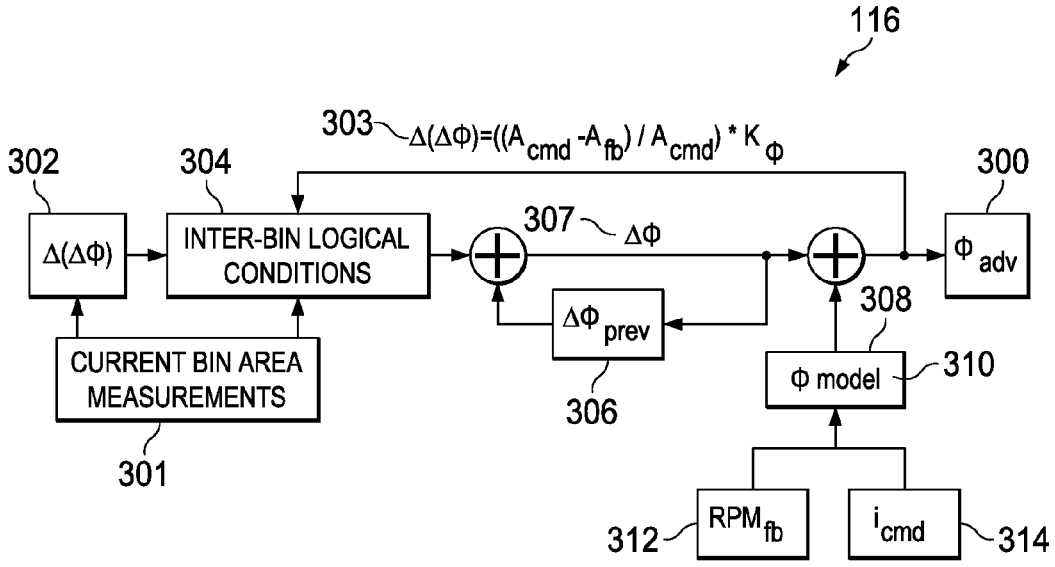

116
303
$\Delta(\Delta\Phi)=((A_{cmd}-A_{fb})/A_{cmd})*K_{\Phi}$
302
304
300
$\Delta(\Delta\Phi)$
INTER-BIN LOGICAL CONDITIONS
307
$\Delta\Phi$
Φ_{adv}
308
$\Delta\Phi_{prev}$
CURRENT BIN AREA MEASUREMENTS
Φ model
310
306
301
312
RPM_{fb}
i_{cmd}
314

FIG. 3

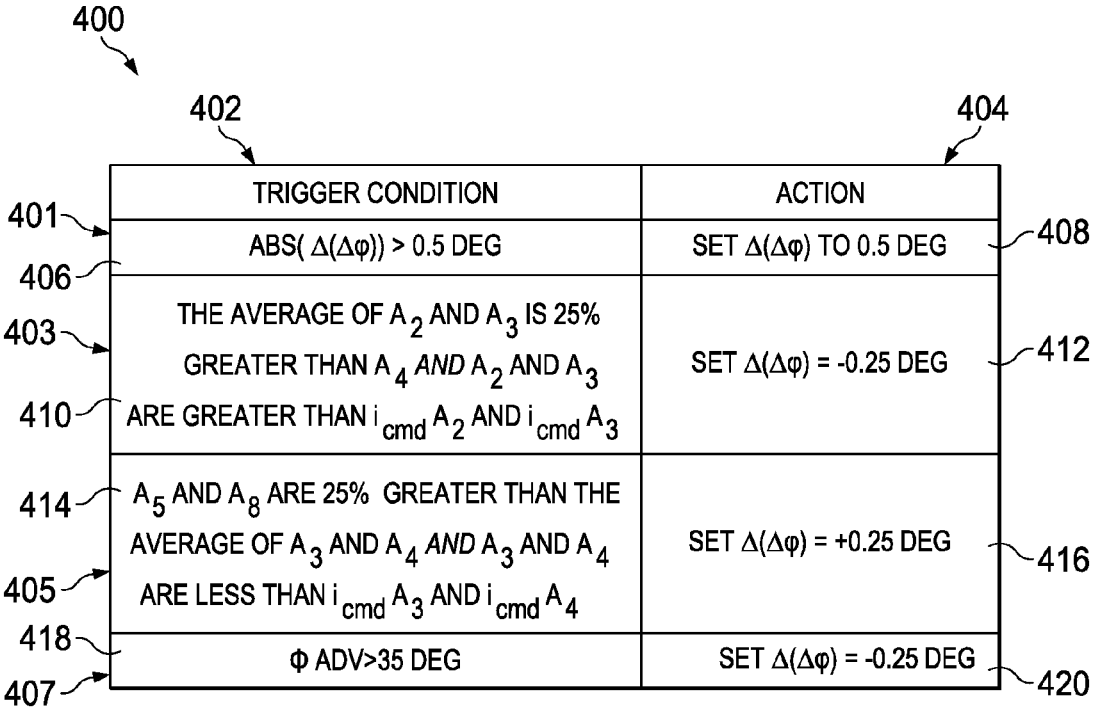

400
402
404
TRIGGER CONDITION
ACTION
401
ABS(Δ(Δφ)) > 0.5 DEG
SET Δ(Δφ) TO 0.5 DEG
408
406
403
THE AVERAGE OF A_2 AND A_3 IS 25% GREATER THAN A_4 *AND* A_2 AND A_3 ARE GREATER THAN i_{cmd} A_2 AND i_{cmd} A_3
SET Δ(Δφ) = -0.25 DEG
412
410
414
A_5 AND A_8 ARE 25% GREATER THAN THE AVERAGE OF A_3 AND A_4 *AND* A_3 AND A_4 ARE LESS THAN i_{cmd} A_3 AND i_{cmd} A_4
SET Δ(Δφ) = +0.25 DEG
416
405
418
Φ ADV>35 DEG
SET Δ(Δφ) = -0.25 DEG
420
407

FIG. 4

FIG. 5

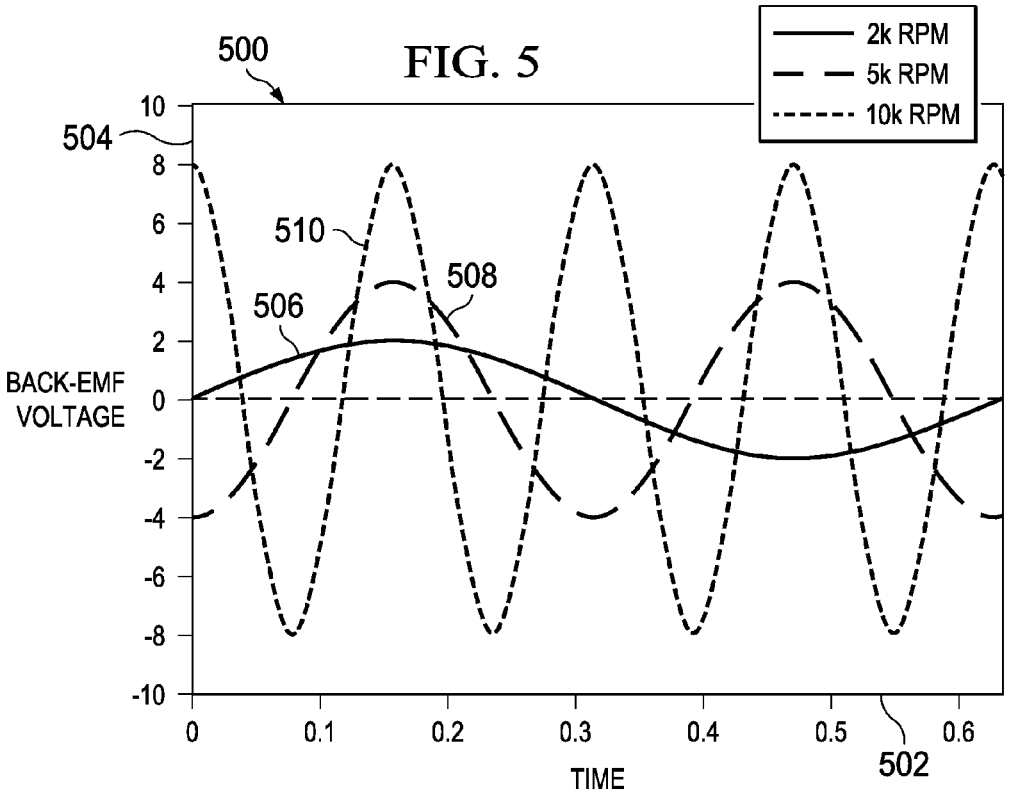
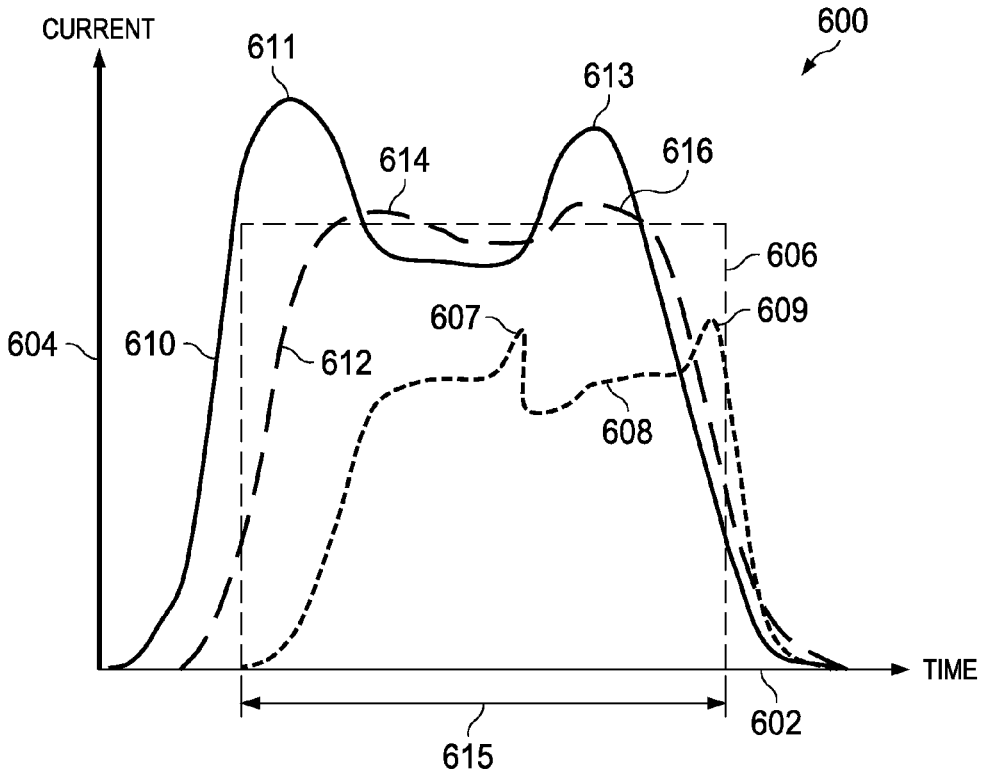

500
2k RPM
5k RPM
10k RPM
504
10
8
6
4
2
0
-2
-4
-6
-8
-10
BACK-EMF VOLTAGE
510
508
506
0
0.1
0.2
0.3
0.4
0.5
0.6
TIME
502

FIG. 6


CURRENT
600
611
613
614
616
606
604
610
607
609
612
608
TIME
602
615

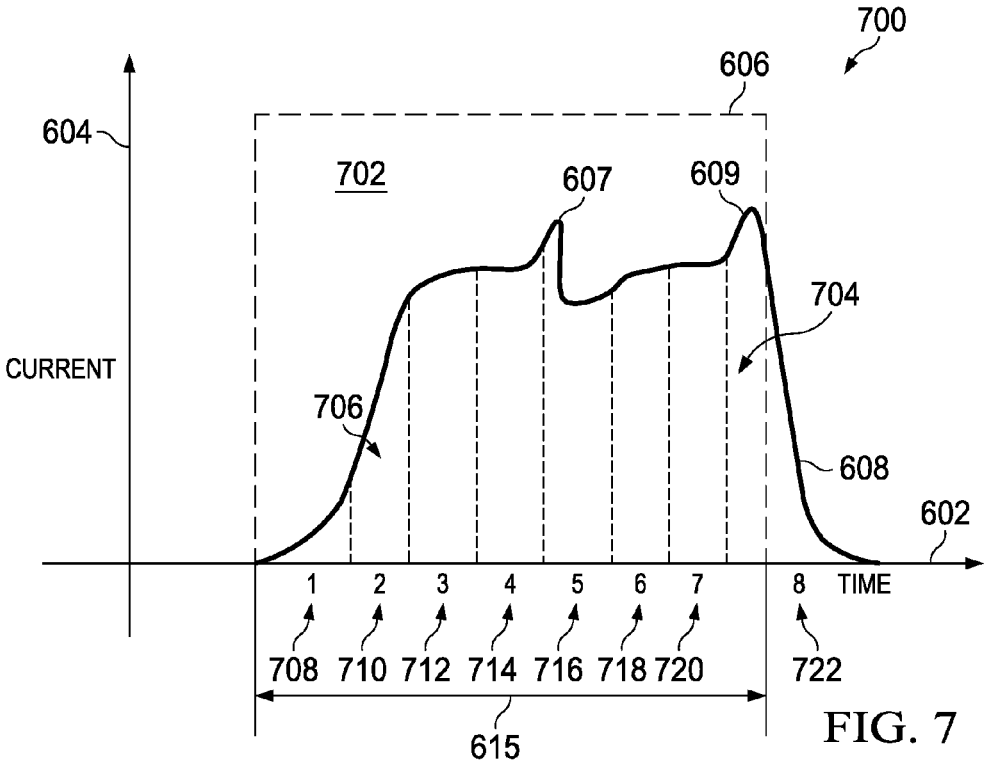

700
606
604
702
607
609
704
CURRENT
706
608
602
1
2
3
4
5
6
7
8
TIME
708
710
712
714
716
718
720
722
615

FIG. 7

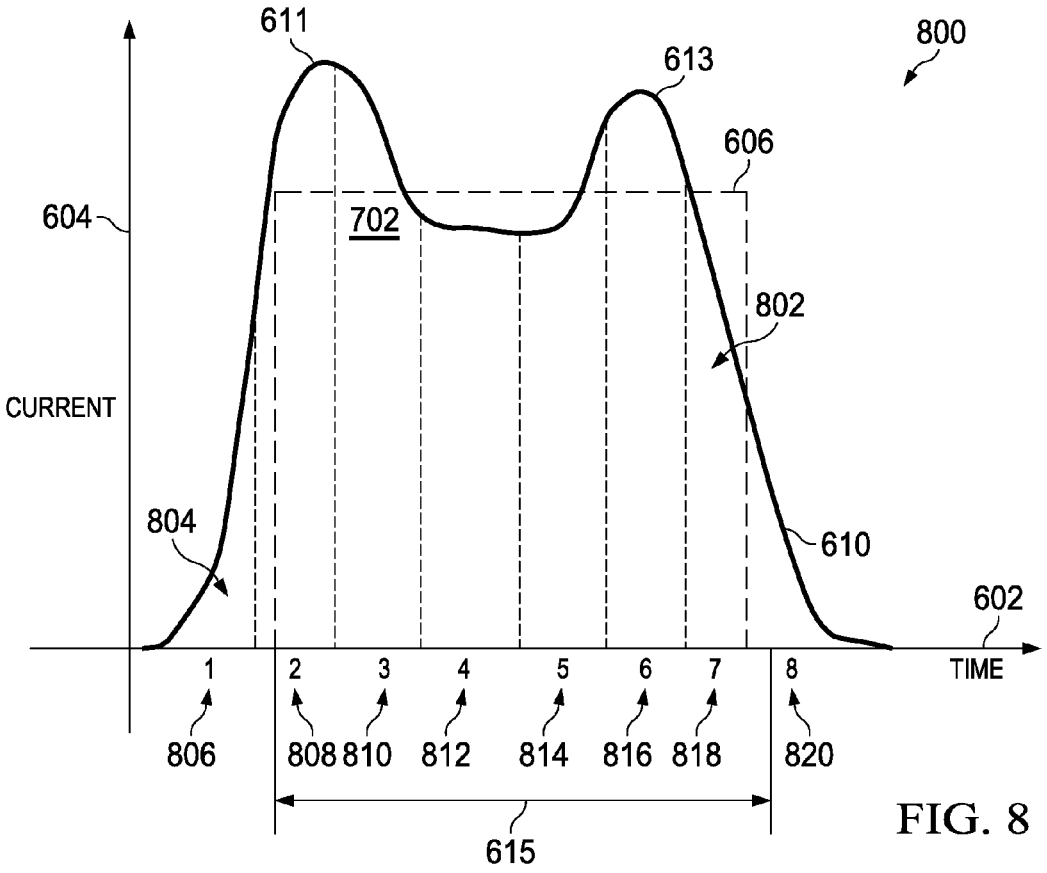

611
800
613
606
604
702
802
CURRENT
804
610
602
1
2
3
4
5
6
7
8
TIME
806
808
810
812
814
816
818
820
615

FIG. 8

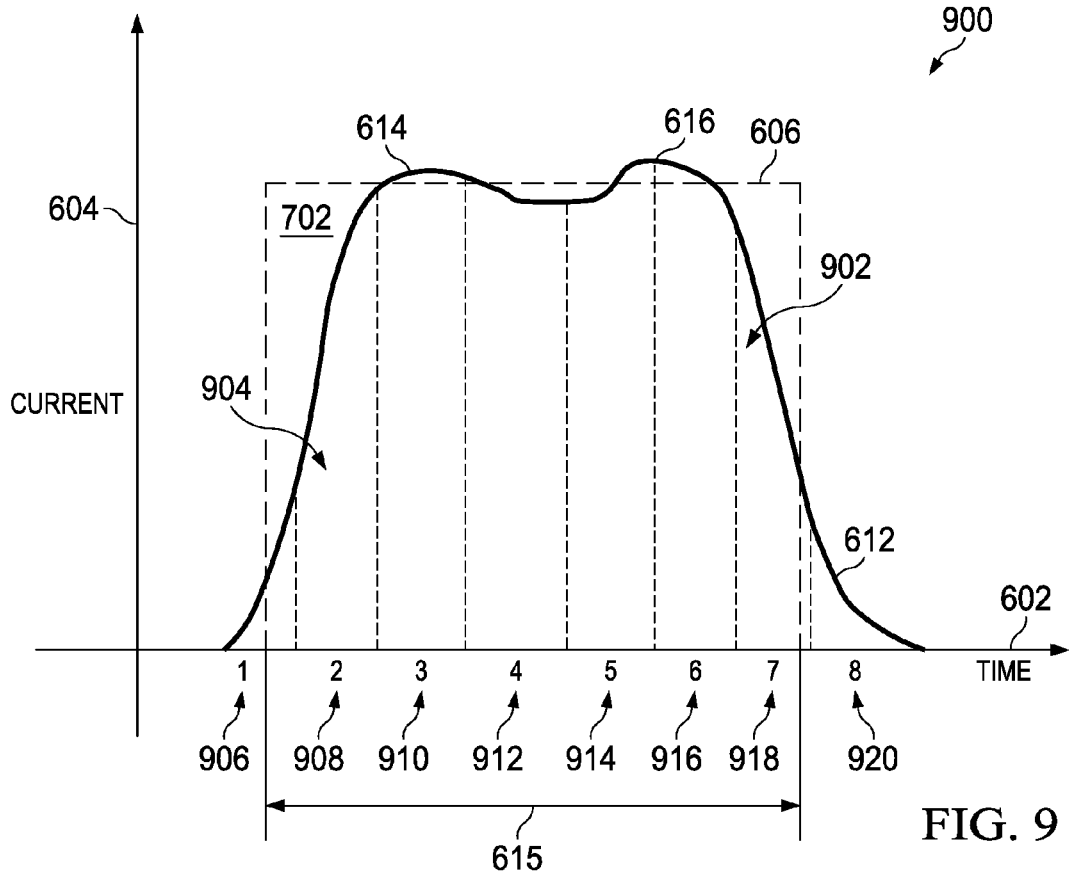

900
614
616
606
604
702
902
CURRENT
904
612
602
1
2
3
4
5
6
7
8
TIME
906
908
910
912
914
916
918
920
615

FIG. 9

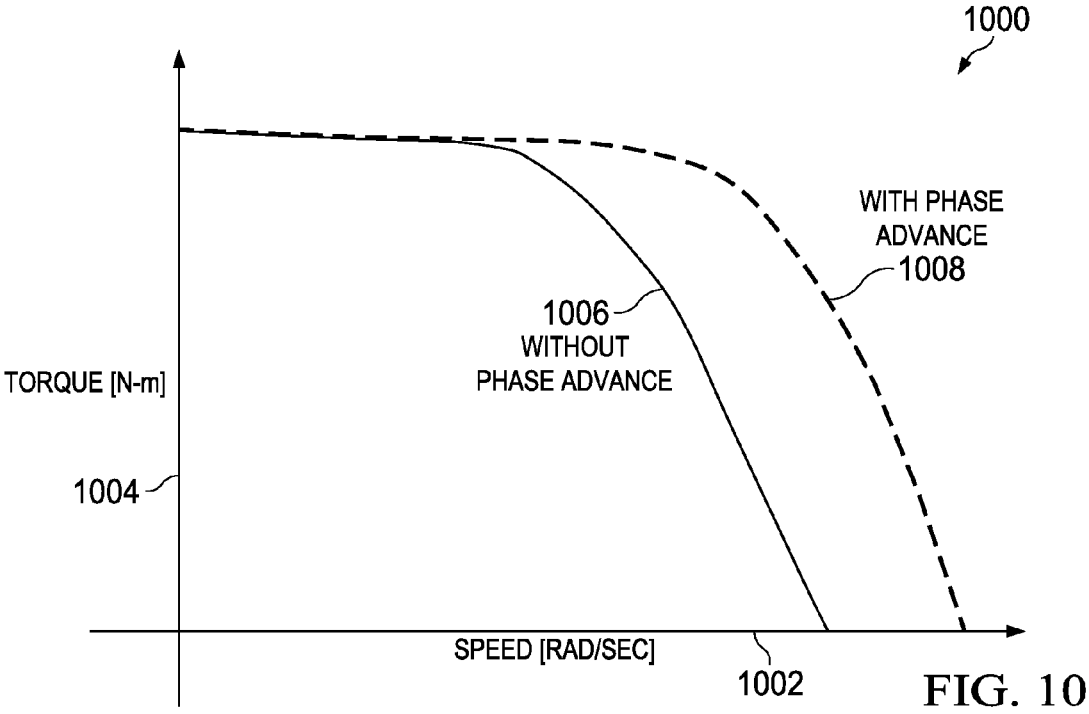

1000
WITH PHASE
ADVANCE
1008
1006
WITHOUT
PHASE ADVANCE
TORQUE [N-m]
1004
SPEED [RAD/SEC]
1002

FIG. 10

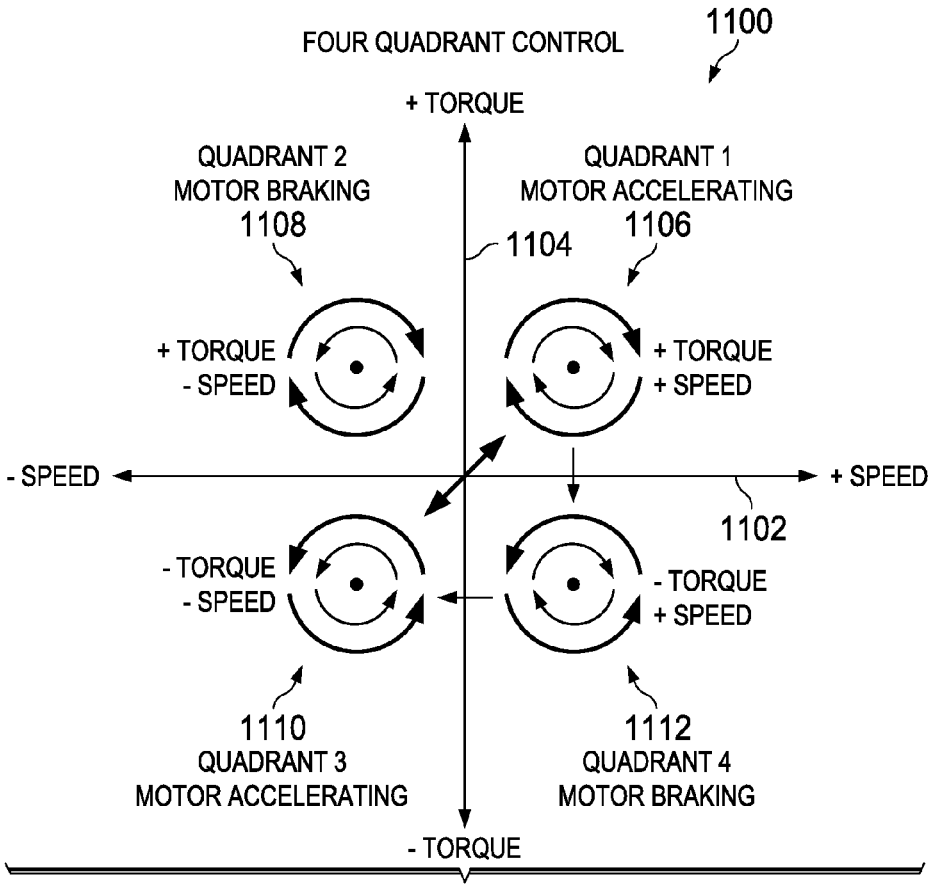

FOUR QUADRANT CONTROL
1100
+ TORQUE
QUADRANT 2
MOTOR BRAKING
1108
QUADRANT 1
MOTOR ACCELERATING
1106
1104
+ TORQUE
- SPEED
+ TORQUE
+ SPEED
- SPEED
+ SPEED
1102
- TORQUE
- SPEED
- TORQUE
+ SPEED
1110
QUADRANT 3
MOTOR ACCELERATING
1112
QUADRANT 4
MOTOR BRAKING
- TORQUE

FIG. 11

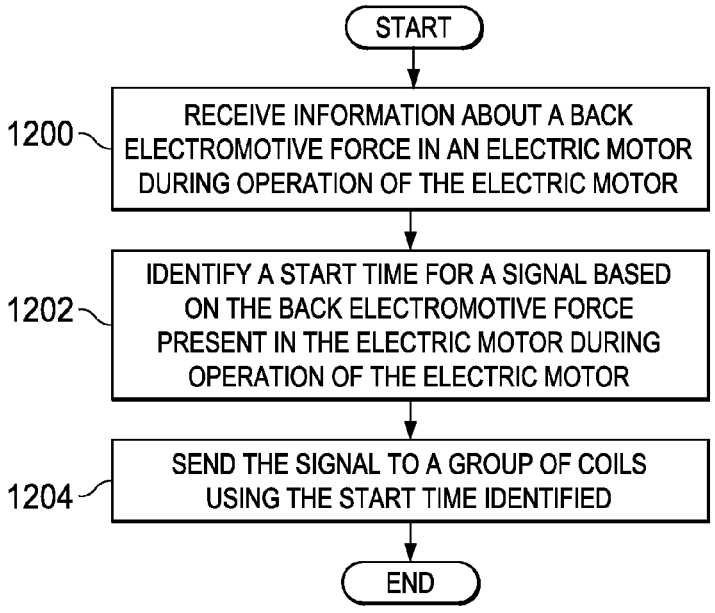
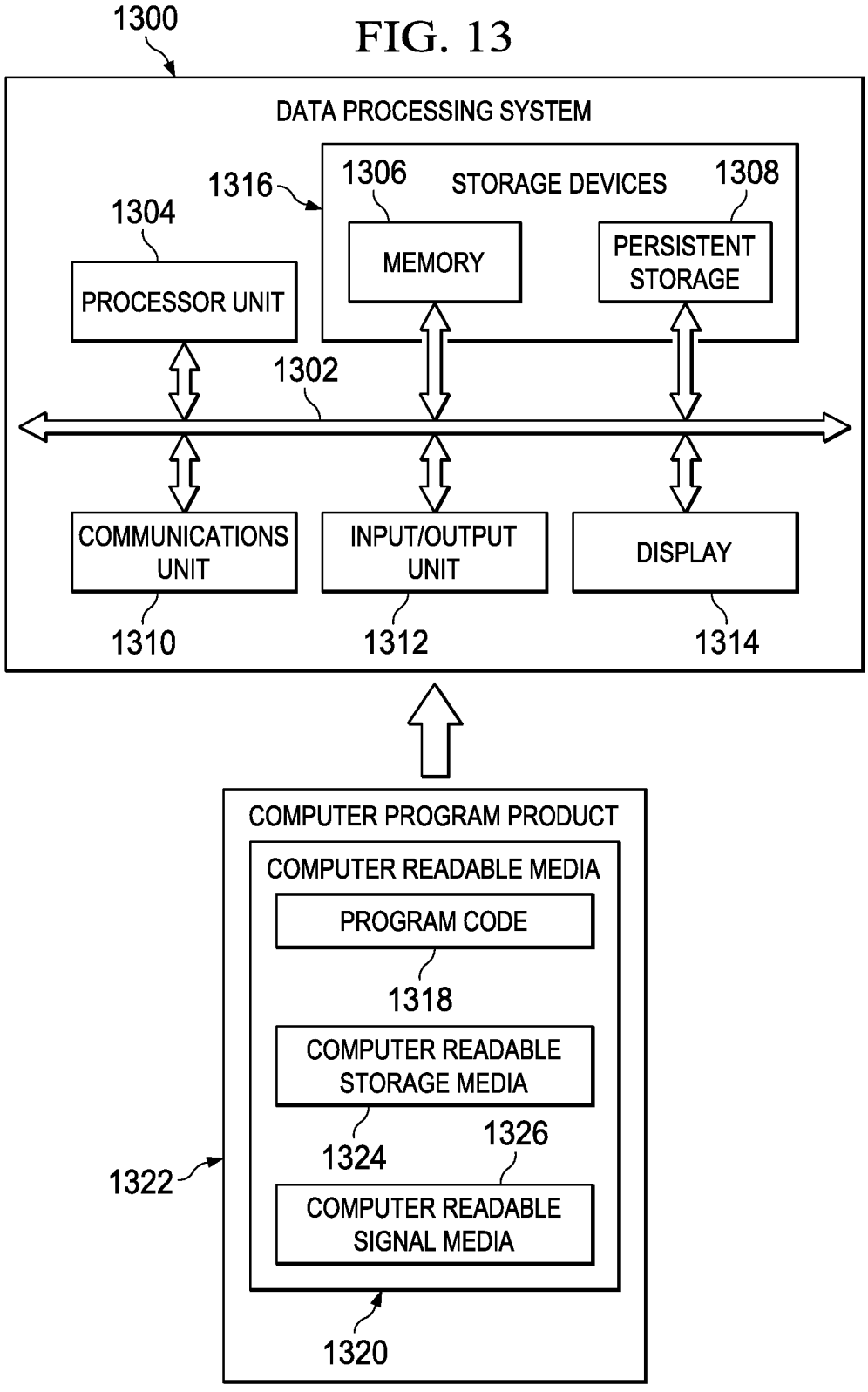

START
1200
RECEIVE INFORMATION ABOUT A BACK ELECTROMOTIVE FORCE IN AN ELECTRIC MOTOR DURING OPERATION OF THE ELECTRIC MOTOR
1202
IDENTIFY A START TIME FOR A SIGNAL BASED ON THE BACK ELECTROMOTIVE FORCE PRESENT IN THE ELECTRIC MOTOR DURING OPERATION OF THE ELECTRIC MOTOR
1204
SEND THE SIGNAL TO A GROUP OF COILS USING THE START TIME IDENTIFIED
END

FIG. 12

FIG. 13


1300
DATA PROCESSING SYSTEM
1316
1306
STORAGE DEVICES
1308
1304
MEMORY
PERSISTENT STORAGE
PROCESSOR UNIT
1302
COMMUNICATIONS UNIT
INPUT/OUTPUT UNIT
DISPLAY
1310
1312
1314
COMPUTER PROGRAM PRODUCT
COMPUTER READABLE MEDIA
PROGRAM CODE
1318
COMPUTER READABLE STORAGE MEDIA
1324
1326
1322
COMPUTER READABLE SIGNAL MEDIA
1320

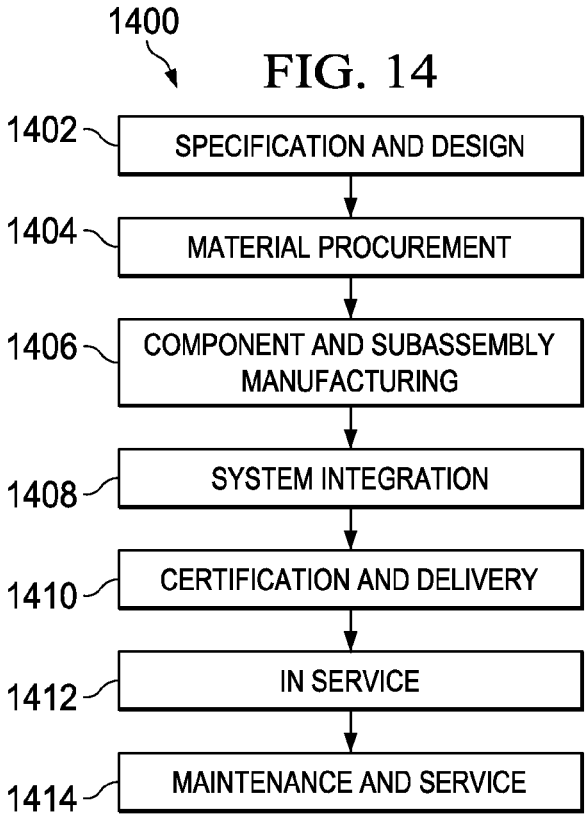

1400
1402
SPECIFICATION AND DESIGN
1404
MATERIAL PROCUREMENT
1406
COMPONENT AND SUBASSEMBLY MANUFACTURING
1408
SYSTEM INTEGRATION
1410
CERTIFICATION AND DELIVERY
1412
IN SERVICE
1414
MAINTENANCE AND SERVICE

FIG. 14

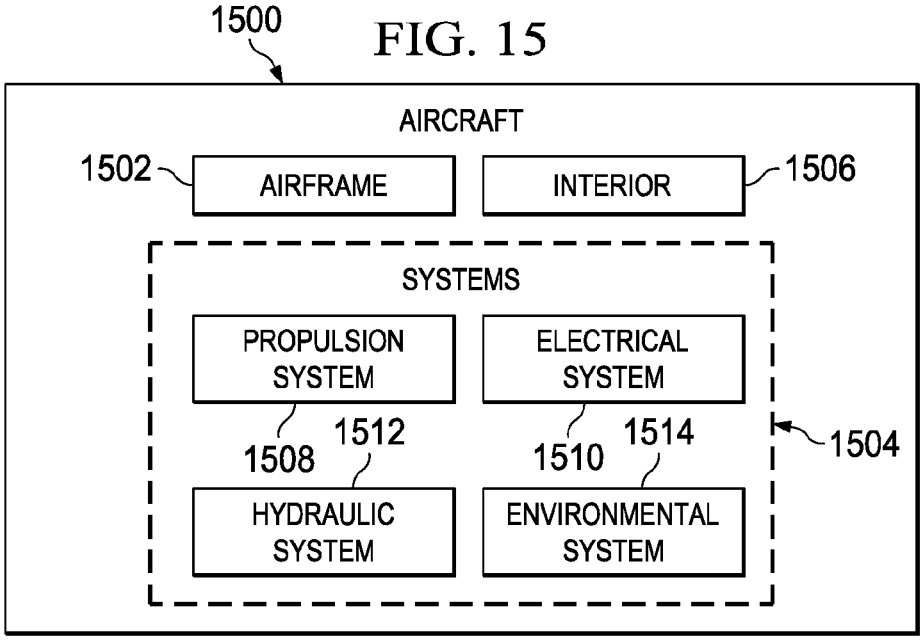

1500
AIRCRAFT
1502
AIRFRAME
INTERIOR
1506
SYSTEMS
PROPULSION SYSTEM
ELECTRICAL SYSTEM
1508
1512
1510
1514
1504
HYDRAULIC SYSTEM
ENVIRONMENTAL SYSTEM

FIG. 15

ELECTRIC MOTOR PHASE CONTROL SYSTEM

BACKGROUND INFORMATION

1. Field

The present disclosure relates generally to electric motor systems and, in particular, to controlling electric motor systems. Still more particularly, the present disclosure relates to a method and apparatus for operating an electric motor phase control system for an electric motor in an electric motor system.

2. Background

An electric motor is a device that converts electrical power into mechanical power. Electric motors are used for various applications. These applications include fans, pumps, tools, disk drives, drills, and other types of devices that may be found in these and other types of platforms.

A brushless electric motor is a commonly used type of electric motor. With brushless electric motors, a controller is configured to change the current in windings in the electric motor. The windings may take the form of coils. The current in the coils may be changed by applying a voltage to the coils that causes a desired amount of current to flow through the coils. In particular, the current is switched at a frequency that changes the amplitude of the current flowing through the windings in phases in a manner that causes the motor to turn. The switching of the current is performed using switches in the form of transistors. When direct current is used to operate the brushless electric motor, the motor may take the form of a brushless direct current electric motor.

The switching of the current in the coils may be referred to as a commutation. A commutation occurs when the current from one coil is moved to another. In other words, a commutation occurs when an energized coil is turned off and a non-energized coil is turned on. Turning "on" a coil refers to a state in which current flows through that coil, while turning "off" a coil refers to a state in which current does not flow through the coil. A commutation is used to rotate the magnetic field configuration for operating a brushless electric motor.

The timing of the current in the coils in a brushless electric motor may be described as a phase angle. A phase angle may be a position of the brushless electric motor relative to the coil plane when the current is flowing through one or more of the coils in the brushless electric motor.

The application of the current to the coils is timed such that the brushless electric motor turns at a desired speed. As the speed of the brushless electric motor increases, a phenomena called back electromotive force (EMF) may affect the performance of the brushless electric motor. The back electromotive force is a voltage which opposes a change in magnetic flux.

Often, the back electromotive force is against the direction of the voltage applied to the coils. This back electromotive force may be present when motion occurs between the coils and a magnetic field.

Back electromotive force increases and decreases over time. With this phenomena, the timing of the application of the voltage to the coils becomes more important as the speed of the brushless electric motor increases. The timing of the current flow to one or more coils may be referred to as commutation time or current start time. In other words, commutation time is the time at which a signal is sent to change the current from one coil to another coil.

As the speed of the brushless electric motor increases, the magnitude of the back electromotive force also increases. As a result, reduced efficiency, current spikes, a reduction in performance, increased noise, and other undesirable effects

may occur. Consequently, the brushless electric motor may not perform as desired. Therefore, it would be desirable to have a method and apparatus that take into account at least some of the issues discussed above, as well as other possible issues.

SUMMARY

In one illustrative embodiment, an apparatus comprises a controller. The controller is configured to identify a start time for a signal based on a back electromotive force present in an electric motor during operation of the electric motor. The start time is for a position of a rotor relative to a group of coils. The controller is further configured to send the signal to the group of coils using the start time identified. An effect of the back electromotive force on the signal is reduced.

In another illustrative embodiment, an electric motor system comprises an electric motor, a sensor system, and a controller. The electric motor has a rotor and a group of coils. The sensor system is configured to generate information about a back electromotive force in the electric motor during operation of the electric motor. The controller is configured to receive the information from the sensor system. The controller is further configured to identify a start time for a current based on the back electromotive force present in the electric motor during operation of the electric motor using the information from the sensor system. The start time is for a position of the rotor relative to the group of coils. The controller is still further configured to send the current to the group of coils using the start time identified. An effect of the back electromotive force on a signal is reduced.

In yet another illustrative embodiment, a method for controlling an electric motor is provided. A start time for a signal is identified based on a back electromotive force present in the electric motor during operation of the electric motor. The start time is for a position of a rotor relative to a group of coils in the electric motor. The signal is sent to the group of coils using the start time identified. An effect of the back electromotive force on the signal is reduced.

The features and functions can be achieved independently in various embodiments of the present disclosure or may be combined in yet other embodiments in which further details can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the illustrative embodiments are set forth in the appended claims. The illustrative embodiments, however, as well as a preferred mode of use, further objectives and features thereof, will best be understood by reference to the following detailed description of an illustrative embodiment of the present disclosure when read in conjunction with the accompanying drawings, wherein:

FIG. **1** is an illustration of a block diagram of an electric motor environment in accordance with an illustrative embodiment;

FIG. **2** is an illustration of a block diagram for controlling a current sent to an electric motor in a manner that reduces the effect of a back electromotive force in the electric motor in accordance with an illustrative embodiment;

FIG. **3** is an illustration of a control law for identifying a phase advance in an electric motor in accordance with an illustrative embodiment;

FIG. **4** is an illustration of inter-bin logical constraints in accordance with an illustrative embodiment;

FIG. **5** is an illustration of a graph of a back electromotive force as a function of speed of an electric motor in accordance with an illustrative embodiment;

FIG. **6** is an illustration of a graph of waveforms in accordance with an illustrative embodiment;

FIG. **7** is an illustration of a graph of a waveform with segments in accordance with an illustrative embodiment;

FIG. **8** is another illustration of a graph of a waveform with segments in accordance with an illustrative embodiment;

FIG. **9** is yet another illustration of a graph of a waveform with segments in accordance with an illustrative embodiment;

FIG. **10** is an illustration of a graph of a torque-speed curve in accordance with an illustrative embodiment;

FIG. **11** is an illustration of four-quadrant control in accordance with an illustrative embodiment;

FIG. **12** is an illustration of a flowchart of a process for controlling an electric motor in accordance with an illustrative embodiment;

FIG. **13** is an illustration of a block diagram of a data processing system in accordance with an illustrative embodiment;

FIG. **14** is an illustration of a block diagram of an aircraft manufacturing and service method in accordance with an illustrative embodiment; and

FIG. **15** is an illustration of a block diagram of an aircraft in which an illustrative embodiment may be implemented.

DETAILED DESCRIPTION

The illustrative embodiments recognize and take into account a number of different considerations. For example, the illustrative embodiments recognize and take into account that the timing of the voltage applied to an electric motor may be changed to reduce the effect of a back electromotive force. This change in timing may take the form of a phase advance. For example, the voltage may be applied to the coils when the position of the rotor relative to the coils is at a particular phase angle. The voltage may be applied at an earlier time prior to the phase angle. In other words, switches may be closed to allow a current to flow through the coils at an earlier time. This change in the flow of current is an example of a phase advance. A phase advance may be used to cause the current to flow through the coils in a desired manner.

The illustrative embodiments also recognize and take into account that the timing of the current flow may be based upon a number of factors such as the load and other suitable factors. A "number of," as used herein with reference to factors, means one or more factors. For example, a number of factors is one or more factors.

The illustrative embodiments recognize and take into account that one manner in which the start time for a current may be selected is based on predetermined values for the start time. These predetermined values may be selected for different speeds of the electric motor. The values may be identified using a model of the electric motor and other components in the electric motor environment. These values may be phase angles in a table. These values are used to determine when to send the current through the coils during the operation of the electric motor. In other words, models may be used to determine start times for sending voltage to the coils to cause a desired amount of current to flow through the coils.

The illustrative embodiments recognize and take into account, however, that these models may not take into account as many factors as desired for a desired level of performance for the electric motor in response to a back electromotive force occurring during the operation of the electric motor. For example, temperature changes, load changes, and other factors may result in the predetermined values not providing a desired level of performance.

Thus, the illustrative embodiments provide a method and apparatus for controlling the operation of the electric motor. In one illustrative example, a controller is configured to identify a start time for a signal based on a back electromotive force present in the electric motor during operation of the electric motor. This start time may be referred to as a commutation time. The start time is for a position of a rotor relative to a group of coils. The controller is further configured to send the signal to the group of coils of the start time identified such that an effect of the back electromotive force on the signal is reduced.

With reference now to the figures and, in particular, with reference to FIG. **1**, an illustration of a block diagram of an electric motor environment is depicted in accordance with an illustrative embodiment. Electric motor environment **100** is an example of an environment in which an illustrative embodiment may be implemented.

Electric motor system **102** in electric motor environment **100** includes a number of different components. As depicted, electric motor system **102** includes electric motor **104**, power supply **106**, and controller **108**.

Electric motor **104** is configured to generate rotary or linear torque or force. In these illustrative examples, electric motor **104** takes the form of brushless direct current electric motor **110**.

Power supply **106** supplies voltage **107** to electric motor **104** through controller **108**. In turn, voltage **107** may cause current **112** to flow through windings in electric motor **104**.

Power supply **106** may take various forms. For example, power supply **106** may be selected from at least one of a battery, a power supply unit that converts alternating current to direct current, an electric generator, or some other suitable component.

As used herein, the phrase "at least one of," when used with a list of items, means different combinations of one or more of the listed items may be used and only one of each item in the list may be needed. For example, "at least one of item A, item B, or item C" may include, without limitation, item A, item A and item B, or item B. This example also may include item A, item B, and item C or item B and item C. Of course, any combinations of these items may be present. In other examples, "at least one of" may be, for example, without limitation, two of item A, one of item B, and ten of item C; four of item B and seven of item C; and other suitable combinations. The item may be a particular object, thing, or a category. In other words, at least one of means any combination of items and number of items may be used from the list but not all of the items in the list are required.

Controller **108** is a hardware device in these illustrative examples. Controller **108** may include software. The hardware may include circuits that operate to perform the operations in controller **108**. In this illustrative example, controller **108** may take the form of an impulse width modulation controller (IWMC) that modulates a switching frequency used to drive switches in the form of transistors that control current **112** sent to electric motor **104**.

In the illustrative examples, the hardware may take the form of a circuit system, an integrated circuit, an application specific integrated circuit (ASIC), a programmable logic device, or some other suitable type of hardware configured to perform a number of operations. With a programmable logic device, the device is configured to perform the number of operations. The device may be reconfigured at a later time or may be permanently configured to perform the number of

operations. Examples of programmable logic devices include, for example, a programmable logic array, a programmable array logic, a field programmable logic array, a field programmable gate array, and other suitable hardware devices. Additionally, the processes may be implemented in organic components integrated with inorganic components and/or may be comprised entirely of organic components excluding a human being. For example, the processes may be implemented as circuits in organic semiconductors.

For example, controller **108** may be implemented in computer system **146**. Computer system **146** includes one or more computers. When more than one computer is present, those computers may communicate with each other through a communications medium such as a network. In other illustrative examples, controller **108** may be implemented in other devices other than computer system **146**.

In this illustrative example, control laws **114** are present in controller **108**. Control laws **114** are processes, functions, or some other mechanism configured to control the operation of electric motor **104**. As depicted, control laws **114** may be implemented in hardware, software, or some combination of the two.

Group of control laws **114** may be used to control operation of electric motor **104** in a desired manner. A "group of," as used herein with reference to items, means one or more items. For example, group of control laws **114** is one or more control laws in control laws **114**.

In this illustrative example, control law **116** in group of control laws **114** is configured to control the sending of signal **126** to coils **118** in electric motor **104**. In particular, control law **116** is configured to control number of switches **119** to send signal **126** to coils **118**.

In the illustrative example, signal **126** is current **112**. Voltage **107** is applied to coils **118** by controller **108** such that current **112** is produced in coils **118**. As depicted, current **112** causes rotor **120** in electric motor **104** to move.

In this example, the movement of rotor **120** is a turning or rotation. Coils **118** are physically associated with a separate structure from rotor **120** in this illustrative example.

When one component is "physically associated" with another component, the association is a physical association in the depicted examples. For example, a first component, coils **118**, may be considered to be physically associated with a second component, a structure, by being secured to the second component, bonded to the second component, mounted to the second component, welded to the second component, fastened to the second component, and/or connected to the second component in some other suitable manner. The first component also may be connected to the second component using a third component. The first component may also be considered to be physically associated with the second component by being formed as part of the second component, extension of the second component, or both.

In this illustrative example, electromotive force (EMF) may be present during the operation of electric motor **104**. In particular, back electromotive force **122** may be present and may oppose voltage **107** supplied by power supply **106**. As speed **124** of electric motor **104** increases, the effect of back electromotive force **122** also increases in this illustrative example. In this example, speed **124** may be for movement **127** of rotor **120** relative to coils **118**.

As depicted, control law **116** in controller **108** may control the sending of signal **126** to coils **118** in a manner that reduces the effect of back electromotive force **122**. In particular, control law **116** in controller **108** may be configured to identify start time **128** for signal **126** based on back electromotive force **122** present in electric motor **104** during operation of electric motor **104**.

In this illustrative example, start time **128** is the time at which a coil in coils **118** is commanded to be turned on. Turning "on" a coil refers to a state in which current **112** flows through that coil. In other words, start time **128** is the time in which current **112** is caused to flow through that coil. Start time **128** is for position **130** of rotor **120** relative to coils **118**. Accordingly, signal **126** may be sent to a single coil or multiple coils in coils **118**.

In this illustrative example, controller **108** is also configured to send signal **126** to coils **118** based on start time **128** identified. The selection of start time **128** is made such that an effect of back electromotive force **122** on signal **126** is reduced. In this manner, when signal **126** takes the form of voltage **107** that causes current **112** to flow through coils **118**, smaller amounts of voltage **107** may be needed to produce a desired level of current **112** in coils **118** when taking into account the presence of back electromotive force **122**.

As a result, the amount of current **112** needed to operate electric motor **104** may be reduced. In this manner, a more efficient operation of electric motor system **102** may occur.

As depicted, electric motor system **102** also may include sensor system **142**. Sensor system **142** is configured to generate information **144** about back electromotive force **122**. Sensor system **142** is configured to send information **144** to controller **108**.

In the illustrative example, sensor system **142** is configured to measure current **112** in coils **118** during operation of electric motor **104**. In one example, sensor system **142** may include one or more Hall effect sensors. In other examples, sensor system **142** may include other suitable types of current sensors.

Information **144** about back electromotive force **122** is generated by sensor system **142** from the measurement of current **112** in coils **118**. As depicted, information **144** may be values measured for current **112** flowing through coils **118**.

With information **144**, controller **108** is configured to change start time **128** based on a change in back electromotive force **122**. For example, as speed **124** of electric motor **104** changes, back electromotive force **122** also may change. For example, at least one of amplitude, period of time, or other characteristics for back electromotive force **122** may change as speed **124** changes for electric motor **104**.

As depicted, controller **108** may identify start time **128** in response to an event. This event may be a periodic event that occurs over a period of a millisecond, ten seconds, three minutes, or some other period of time. The event also may be a non-periodic event such as a signal input by an operator for controller **108** or received from some other device. As a result, start time **128** may be changed during the operation of electric motor **104** in a manner that reduces the effects of back electromotive force **122**.

Thus, more efficient control of electric motor **104** may be performed. When start time **128** is identified based on position **130** in the form of a phase, electric motor system **102** may be an electric motor phase control system. In other words, start time **128** may occur when rotor **120** in electric motor **104** has a particular phase for position **130**.

Turning next to FIG. **2**, an illustration of a block diagram for controlling a current sent to an electric motor in a manner that reduces the effect of a back electromotive force in the electric motor is depicted in accordance with an illustrative embodiment. As depicted, controller **108** is configured to identify start time **128** during the operation of electric motor **104** in FIG. **1** using information **144**. Start time **128** may be

selected based on position **130** of rotor **120** in electric motor **104** relative to coils **118** in FIG. **1**.

In the illustrative example, controller **108** identifies start time **128** based on a change in back electromotive force **122** seen in FIG. **1**. The change may be identified based on information **144** received during operation of electric motor **104**.

As depicted, information **144** is used by controller **108** to identify waveform **200** for current **112** caused by signal **126** in FIG. **1**. In particular, information **144** is used by controller **108** to identify waveform **200** for current **112** caused by voltage **107** applied to coils **118**. Waveform **200** is affected by back electromotive force **122** and changes as back electromotive force **122** changes.

As depicted, waveform **200** has number of characteristics **202**. In the illustrative example, number of characteristics **202** may include, for example, amplitude **204**, start time **206**, period of time **208**, and other characteristics for waveform **200**.

Additionally, commanded waveform **210** is present for electric motor **104**. Commanded waveform **210** is a waveform resulting from commanded current **212**. As depicted, commanded waveform **210** is an example of a waveform that occurs for current **112** flowing in coils **118** when the effect of back electromotive force **122** in sending current **112** through coils **118** is reduced. This reduction may result in electric motor **104** operating as desired.

In this illustrative example, commanded current **212** is a command for one or more values. Commanded current **212** may be used to change the speed at which electric motor **104** operates.

Commanded current **212** may specify number of characteristics **214** for causing current **112** in coils **118**. For example, number of characteristics **214** may include commanded amplitude **216**, period of time **218**, and other suitable characteristics for commanded waveform **210**.

In this illustrative example, waveform **200** may have amplitude **204**, which may be desired amplitude **220**, over period of time **208** based on a selection of start time **128**. For example, desired amplitude **220** for waveform **200** may be substantially equal to commanded amplitude **216**. As a result, current **112** as commanded for electric motor **104** may be about the same as current **112** in coils **118** in electric motor **104**.

In this example, in identifying start time **128**, controller **108** compares waveform **200** to commanded waveform **210**. Controller **108** identifies first area **222** under waveform **200** and second area **224** under commanded waveform **210**. Controller **108** identifies start time **128** based on a difference between first area **222** and second area **224**.

For example, controller **108** is configured to advance start time **128** to an earlier start time if first area **222** is less than second area **224** by a selected amount. In these illustrative examples, start time **128** may be advanced to an earlier start time by increasing the phase in which current **112** is caused to flow through coils **118**.

As depicted, first area **222** may be identified by dividing waveform **200** into segments **226**. First area **222** may then be identified from segments **226**. Dividing waveform **200** into segments **226** may be performed when waveform **220** has an irregular shape. In a similar fashion, second area **224** also may be identified by dividing commanded waveform **210** into segments **228**.

The illustration of electric motor environment **100** and the different components in FIG. **1** and FIG. **2** is not meant to imply physical or architectural limitations to the manner in which an illustrative embodiment may be implemented. Other components in addition to or in place of the ones illustrated may be used. Some components may be unnecessary. Also, the blocks are presented to illustrate some functional components. One or more of these blocks may be combined, divided, or combined and divided into different blocks when implemented in an illustrative embodiment.

For example, controller **108** may be configured to control one or more electric motors in addition to electric motor **104**. Further, controller **108** may take other forms other than an impulse width modulation controller. For example, controller **108** also may be a pulse width modulation controller in some illustrative examples.

Additionally, although number of switches **119** are shown in controller **108** in this example, in other illustrative examples, controller **108** may comprise only control law **116**. In this case, number of switches **119** may be a separate component.

As another example, although the movement of rotor **120** relative to coils **118** has been described as a rotational movement, other types of movement may be present when electric motor **104** takes other forms. For example, electric motor **104** also may be selected from one of a reluctance motor, a variable reluctance motor, and a virtual ellipse device. As an example, when electric motor **104** is a virtual ellipse device, movement **127** of rotor **120** may be a nutating or wobbling movement rather than a rotational movement.

With reference next to FIG. **3**, an illustration of a control law for identifying a phase advance in an electric motor is depicted in accordance with an illustrative embodiment. In this depicted example, one example of an implementation for control law **116** in FIG. **1** is shown.

As depicted, control law **116** is configured to identify phase advance (ϕadv) **300**. Phase advance **300** is an example of position **130** of rotor **120** used to identify start time **128** for current **112** to flow through coils **118** in electric motor **104** in FIG. **1**.

Control law **116** includes a number of different components. For example, control law **116** includes current bin area measurements **301**, phase correction ($\Delta(\Delta\phi)$) **302**, inter-bin logical conditions **304**, previous phase advance offset ($\Delta\phi_{prev}$) **306**, phase advance offset ($\Delta\phi$) **307**, and model **308**.

Phase correction **302** may be calculated from current bin area measurements **301**. Current bin area measurements **301** include waveform area measurements of commanded current **212** in FIG. **2** and current **112** in this illustrative example. In other words, current bin area measurements **301** include A_{cmd} and A_{cfb}. Current bin area measurements **301** are used to calculate phase correction **302** and compare A_{cmd} and A_{cmd} in inter-bin logical conditions **304**.

In this illustrative example, phase correction **302** may be calculated using equation **303**, where A_{cmd} is the commanded area, A_{fb} is the area under the feedback curve, or the measured area, and K_{ϕ} is a constant.

As depicted, phase correction **302** may then be compared to inter-bin logical conditions **304**. Phase correction **302** is compared to inter-bin logical conditions **304** to determine whether inconsistencies exist and changes are needed. Changes may be needed if phase correction **302** violates any of inter-bin logical conditions **304**.

After the comparison of phase correction **302** and inter-bin logical conditions **304** is made, phase correction **302** is added to previous phase advance offset **306** to calculate phase advance offset **307**. Previous phase advance offset **306** is the phase advance offset from the previous iteration of the logical process according to control law **116**.

As illustrated, the rate at which phase advance offset **307** may increase or decrease depends on the proportional constant ($K\phi$) in equation **303**. Accordingly, phase advance offset

307 may change over time with the effect of trying to "pull" the current waveform area, A_{fb}, to the commanded current area, A_{cmd}, with phase correction **302** being proportional to the difference between A_{cmd} and $A_{fb\ in}$ equation **303**.

In this illustrative example, the closer A_{cmd} and A_{fb} become, the smaller phase correction **302** will be. Moreover, phase correction **302** is also linearly proportional to constant K_{Φ}. As a result, the magnitude of phase correction **302** also may be scaled by adjusting this constant. Each time the cycle is repeated, a new phase correction **302** term is added to previous phase advance offset **306** to arrive at a new phase advance offset **307**.

Once phase advance offset **307** is determined, the result may then be added to the output of model **308**. Model **308** may be a mathematical model that provides a starting point for the phase advance calculation in this example.

As illustrated, model **308** may provide a baseline phase advance value (ϕ_{model}) **310**. Baseline phase advance value **310** may be an estimated phase advance value used to minimize convergence time of the system. In other words, with the use of model **308**, it may take less time to reach a desired phase advance for operation of the electric motor than if model **308** is not used. In other examples, model **308** may be omitted.

Model **308** may include a number of different inputs. In this example, model **308** includes measured revolutions per minute (RPM_{fb}) **312** and measure current (i_{cmd}) **314**.

The result of the sum of phase advance offset **307** and baseline phase advance value **310** is phase advance **300**. Phase advance **300** is then used by controller **108** to adjust the start time **128**.

With reference to FIG. **4**, an illustration of inter-bin logical constraints is depicted in accordance with an illustrative embodiment. In this depicted example, table **400** shows different types of inter-bin logical conditions **304** for comparison with phase correction **302** from FIG. **3**.

In this illustrative example, column **402** and column **404** are present in table **400** of inter-bin logical conditions **304**. Column **402** represents trigger conditions and column **404** represents actions taken in response to each of the trigger conditions. In particular, row **401**, row **403**, row **405**, and row **407** represent four trigger conditions and action pairs in this illustrative example.

In one example, trigger condition **406** occurs when the absolute amount of phase correction is greater than 0.5 degrees. As a result, action **408** is implemented such that phase correction **302** in FIG. **3** is limited to a maximum of about 0.5 degrees per step.

As another example, trigger condition **410** occurs when the average of A_2 and A_3 is 25% greater than A_4, and A_2 and A_3 are greater than $i_{cmd}A_2$ and $i_{cmd}A_3$, where A_1, A_2, and A_3 are areas of bins under the commanded waveform. These logical conditions may indicate that phase advance **300** is too large. In response, action **412** may be implemented to set phase correction **302** to about −0.25 degrees and thus, reduce phase advance **300**.

In another example, trigger condition **414** may occur when A_5 and A_8 are about 25 percent greater than the average of A_3 and A_4, and A_3 and A_4 are less than $i_{cmd}A_3$ and $i_{cmd}A_4$. These conditions may indicate that phase advance **300** is too small. Action **416** is then taken to increase phase advance **300** such that phase correction **302** is set to about 0.25 degrees.

In still another example, trigger condition **418** may occur when phase advance **300** is greater than about 35 degrees. In this example, 35 degrees may be a maximum desired value for phase advance **300**. In other examples, the maximum desired value for phase advance **300** may be 5 degrees, 25 degrees, 45 degrees, or some other suitable value. In response to trigger condition **418**, action **420** may be implemented to set phase correction **302** to −0.25 degrees.

Table **400** illustrates only a few examples of inter-bin logical conditions **304**. A number of additional inter-bin logical conditions **304** may be input into control law **116** in FIG. **1**, depending on the functionality involved.

Turning now to FIG. **5**, an illustration of a graph of a back electromotive force as a function of speed of an electric motor is depicted in accordance with an illustrative embodiment. In this illustrative example, graph **500** illustrates a back electromotive force that may be present in an electric motor, such as electric motor **104** in FIG. **1**, during operation of the electric motor.

In graph **500**, X-axis **502** represents time. Y-axis **504** represents the voltage for a back electromotive force.

As depicted, line **506**, line **508**, and line **510** represent the back electromotive force present for different speeds of the electric motor. In this example, line **506** represents the back electromotive force present when the electric motor operates at about 2000 revolutions per minute (RPM), line **508** represents the back electromotive force present when the electric motor operates at about 5000 revolutions per minute, and line **510** represents the back electromotive force present when the electric motor operates at about 10,000 revolutions per minute.

As can be seen, the magnitude of the back electromotive force increases as the speed of the electric motor increases. Additionally, the period of time for the back electromotive force also reduces as the speed of electric motor increases. Thus, if a current is sent to coils in an electric motor and an electromotive force is present, the electric motor may not perform as desired. For example, the electric motor may not carry the current at the speed desired, more current than desired may be needed to operate the electric motor, and other effects may occur.

Turning next to FIG. **6**, an illustration of a graph of waveforms is depicted in accordance with an illustrative embodiment. As depicted, graph **600** includes x-axis **602** and y-axis **604**. X-axis **602** represents time, while y-axis **604** represents current. This current may be commanded current or actual current, as represented by the different waveforms in graph **600**.

In this illustrative example, line **606**, line **608**, line **610**, and line **612** represent waveforms for different currents over a number of commutation periods. Distance **615** along x-axis **602** represents two commutation periods in this example. Accordingly, each of line **606**, line **608**, line **610**, and line **612** represents waveforms shown over two commutation periods.

As illustrated, line **606** represents a waveform for a commanded current. This commanded current may be one example of an implementation for commanded current **212** in FIG. **2**. It may be desirable to operate electric motor **104** in FIG. **1** such that the actual current is substantially equal to the commanded current. With the back electromotive force, however, control law **116** is needed to determine the desired phase advance to provide a current that is as close as possible to commanded current **212**. Line **608**, line **610**, and line **612** represent waveforms for different phase advance values in this examples.

As depicted, line **608** represents a waveform with no phase advance. In this instance, commutation began later than desired. Control law **116**, as described above, is not used to determine the desired phase advance in this example.

Operation of electric motor **104** under these conditions may be undesirable. As shown, a waveform for current with no phase advance does not reach the commanded current of

line **606**. The current values along line **608** are substantially less than the commanded current values shown along line **606**. This scenario leads to electric motor **104** being unable to operate at the commanded speed or load. In other words, the commanded revolutions per minute and torque may be more than electric motor **104** could produce without phase advance.

Peak **607** and peak **609** in line **608** show spikes in the level of current for an electric motor with no phase advance. Peak **607** occurs toward the end of the first commutation period, while peak **609** occurs toward the end of the second commutation period. In this example, peak **607** and peak **609** are a result of the back electromotive force decreasing on the back side of the sine wave. Without the use of control law **116**, the back electromotive force rapidly drops off and leads to an increase in current as the control law tries to compensate.

As illustrated, line **610** represents a waveform for a current that has a phase advance greater than desired. In this instance, commutation is initiated sooner than desired, causing a rapid increase in the current before the back electromotive force becomes large enough in amplitude to slow the ascent of the current. In other words, a greater than desired phase advance may lead to a current "overshoot," where the current exceeds the commanded current, as shown by peak **611** and peak **613**. Peak **611** and peak **613** are undesired in these illustrative examples because these peaks represent inefficiencies in electric motor system **102**. For example, electric motor **104** may use more power than needed to operate as desired.

In this illustrative example, line **612** represents a waveform for current with a desired phase advance. As shown, line **612** most closely resembles line **606** for commanded current. As a result, electric motor **104** may operate more efficiently when the waveform resembles line **612** than when the waveform resembles line **608** or line **610**.

In this example, the current represented by line **612** may meet the commanded current in line **606** without incurring large overshoots. While peak **614** and peak **616** still occur, these peaks do not lead to large inefficiencies in electric motor **104**. With the use of control law **116**, a desired phase advance may be calculated and applied by controller **108** in FIG. **1**.

In FIG. **7**, an illustration of a graph of a waveform with segments is depicted in accordance with an illustrative embodiment. In this depicted example, graph **700** shows line **606** and line **608** from FIG. **6**.

As illustrated, area **702** represents the total area under line **606**. Area **702** may be calculated as the total area under the commanded current curve, or A_{cmd}. Area **702** may then be compared to area **704** to determine whether area **702** is substantially equal to area **704** within selected tolerances. If area **704** is less than area **702**, additional phase advance may be needed. If area **704** is more than area **702**, less phase advance may be needed.

In this example, area **704** represents the total area under line **608** and may be calculated as the total area under the actual current curve, or A_{fb}. Area **704** may be separated into segments **706**. Segments **706** include segments **708**, **710**, **712**, **714**, **716**, **718**, **720**, and **722** under line **608**. The corresponding areas for each of segments **708**, **710**, **712**, **714**, **716**, **718**, **720**, and **722** are A_1, A_2, A_3, A_4, A_5, A_6, A_7, and A_8, respectively. Area **704** may be approximated by calculating the areas A_1-A_8 and adding areas A_1-A_8. Although eight segments are shown in this illustrative example, other numbers of segments **706** may be used. For example, one segment, five segments, twelve segments, or some other number of segments may be present in area **704**. These segments may be known as "bins."

In this example, segments **706** may be used to provide a more accurate comparison of area **702** and area **704**. Areas A_1-A_8 also may provide additional information to controller **108** about the waveform for line **608**. For example, the area of the different segments **706** may be compared with one another to construct a waveform profile. In this example, peak **607** and peak **609** occur toward the end of the waveform. By comparing segments **706**, a determination of where peak **607** and peak **609** are located may inform controller **108** to increase the phase advance as desired.

As illustrated, area **704** is less than area **702**. In particular, area **704** with segments **708**, **710**, **712**, **714**, **716**, **718**, **720**, and **722** is less than area **702**. As a result, controller **108** may determine that additional phase advance is needed to provide a current that resembles the commanded current of line **606**.

After area **702** and **704** are calculated, a relative difference between area **702** and area **704** is calculated using equation $(A_{cmd}-A_{fb})/A_{cmd}$ and then multiplied by a gain constant, $K\phi$, as shown in equation **303** in FIG. **3**. The result is phase correction $\Delta(\Delta\phi)$ **302**.

In FIG. **8**, another illustration of a graph of a waveform with segments is depicted in accordance with an illustrative embodiment. In this depicted example, graph **800** shows line **606** and line **610** from FIG. **6**.

In this example, area **802** represents the total area under line **610** and may be calculated as the total area under the actual current curve, or A_{fb}. Area **802** may be separated into segments **804**. Segments **804** include segments **806**, **808**, **810**, **812**, **814**, **816**, **818**, and **820** under line **610**. The corresponding areas for each of segments **806**, **808**, **810**, **812**, **814**, **816**, **818**, and **820** are A_1, A_2, A_3, A_4, A_5, A_6, A_7, and A_8, respectively. Area **802** may be approximated by calculating the areas A_1-A_8 and adding areas A_1-A_8.

In this example, segments **804** may be used to provide a more accurate comparison of area **702** and area **802**. Areas A_1-A_8 also may provide additional information to controller **108** in FIG. **1** about the waveform for line **610**. For example, large segments near the beginning of the waveform in line **610** may indicate that the phase advance is larger than desired. As an example, area A_2 and A_3 are larger than area A_1 and A_4. From this information, controller **108** may make a determination that peak **611** is present in line **610**. If area A_2 and A_3 are larger than the area for the corresponding portion of area **702** of line **606**, more phase advance may be present than desired. As a result, controller **108** may adjust the phase advance based on comparisons between segments **804** using inter-bin logical conditions **304** in FIG. **4**.

As illustrated, area **802** is greater than area **702**. In particular, area **802** with segments **806**, **808**, **810**, **812**, **814**, **816**, **818**, and **820** is greater than area **702**. As a result, controller **108** may determine that less phase advance is needed to provide a current that resembles the commanded current of line **606**.

After area **702** and area **802** are calculated, a relative difference between area **802** and area **702** is calculated using equation $(A_{cmd}-A_{fb})/A_{cmd}$ and then multiplied by a gain constant, $K\phi$, as shown in equation **303** in FIG. **3**. The result is phase advance correction $\Delta(\Delta\phi)$ **302**.

Turning next to FIG. **9**, yet another illustration of a graph of a waveform with segments is depicted in accordance with an illustrative embodiment. In this depicted example, graph **900** shows line **606** and line **612** from FIG. **6**.

Once a desired phase advance value, ϕadv, has been calculated using control law **116** in FIG. **1**, the waveform should converge to the shape approximated by line **612**. In this case, area **902** in segments **904** may be substantially equal to area **702** within selected tolerances. In particular, area **902** with segments **906**, **908**, **910**, **912**, **914**, **916**, **918**, and **920** may be substantially equal to area **702**. As a result, the value of the actual current may be close to the value of the commanded

current and electric motor **104** in FIG. **1** may be operating efficiently, taking into account the back electromotive force.

As depicted, the waveform and phase advance value may remain in the state shown in FIG. **9** until the operating conditions of electric motor **104** change. For example, upon changing revolutions per minute or load, the phase advance will adapt according to control law **116**. In this manner, the illustrative embodiments provide a closed-loop control law for determining a desired phase advance in electric motor **104**.

Referring to FIG. **10**, an illustration of a graph of a torque-speed curve is depicted in accordance with an illustrative embodiment. Graph **1000** shows an example of the performance potential of two electric motors. In this illustrative example, x-axis **1002** represents speed in radians per second, and y-axis **1004** represents torque in newton meters.

It may be desirable to extend the torque-speed curve for electric motor **104** in FIG. **1** by choosing a desired phase advance value. Without using phase advance, the maximum power output (power=speed*torque) is limited.

In this illustrative example, line **1006** shows a torque-speed curve for an electric motor without phase advance, while line **1008** shows a torque-speed curve for an electric motor with phase advance according to control law **116**. For an electric motor without phase advance, as the speed increases, the back electromotive force increases, and the torque decreases. This situation may lead to operation of the electric motor in an undesired manner.

As shown, the electric motor with phase advance according to control law **116** may operate more desirably than the electric motor with no phase advance. More torque is available at higher speeds than with the electric motor of line **1006**. Phase advance allows the commutation to occur earlier, therefore allowing current **112** in coils **118** to increase before back electromotive force **122** slows the increase in current **112**.

With reference now to FIG. **11**, an illustration of four-quadrant control is depicted in accordance with an illustrative embodiment. In this illustrative example, electric motor system **102** in FIG. **1** may be used in multiple instances. In particular, controller **108** may be used to control electric motor **104** to operate in the four quadrants as illustrated by graph **1100**. Controller **108** is configured to control operation of electric motor **104** in one or more of the four quadrants illustrated in graph **1100**.

As depicted, graph **1100** illustrates torque versus speed. X-axis **1102** represents speed. Y-axis **1104** represents torque. In this illustrative example, first quadrant **1106**, second quadrant **1108**, third quadrant **1110**, and fourth quadrant **1112** are illustrated. First quadrant **1106** represents acceleration of the motor in which speed is in a first direction with torque in a first direction. Second quadrant **1108** represents motor braking in which torque is in the reverse direction while speed is in the forward direction. Third quadrant **1110** represents acceleration of the motor with torque in a second direction and speed in a second direction. Fourth quadrant **1112** represents braking of the motor running in reverse. In this quadrant, the speed is in the reverse direction while the torque is in the forward direction.

The different electric motors in the illustrative examples may be controlled to operate in one or more of the four different quadrants described in FIG. **11**. For example, controller **108** in FIG. **1** may control electric motor **104** to operate in one or more of first quadrant **1106**, second quadrant **1108**, third quadrant **1110**, and fourth quadrant **1112**.

With reference now to FIG. **12**, a flowchart of a process for controlling an electric motor is depicted in accordance with an illustrative. The process illustrated in FIG. **12** may be implemented in electric motor system **102** in electric motor environment **100** to control the operation of electric motor **104** in FIG. **1**.

The process begins by receiving information about a back electromotive force in an electric motor during operation of the electric motor (operation **1200**). In this illustrative example, the information is a measurement of a current of the coils for generating the information about the back electromotive force.

The process then identifies a start time for a signal based on the back electromotive force present in the electric motor during operation of the electric motor (operation **1202**). In this example, the signal is a current sent to the coils in the electric motor. In this illustrative example, the start time is for a position of a rotor relative to a group of coils in the electric motor. This position may be described using a phase angle which also may be referred to as a phase.

The process sends the signal to a group of coils using the start time identified (operation **1204**), with the process terminating thereafter. In this manner, the start time may be selected to reduce an effect of the back electromotive force on the signal sent to the coils.

The different operations in FIG. **12** may be repeated any number of times during the operation of an electric motor. These operations may be performed to dynamically adjust the start time or phase for sending current to the electric motor in a manner that reduces the effects of a back electromotive force in the electric motor.

The flowcharts and block diagrams in the different depicted embodiments illustrate the architecture, functionality, and operation of some possible implementations of apparatuses and methods in an illustrative embodiment. In this regard, each block in the flowcharts or block diagrams may represent a module, a segment, a function, and/or a portion of an operation or step. For example, one or more of the blocks may be implemented as program code, in hardware, or a combination of the program code and hardware. When implemented in hardware, the hardware may, for example, take the form of integrated circuits that are manufactured or configured to perform one or more operations in the flowcharts or block diagrams. When implemented as a combination of program code and hardware, the implementation may take the form of firmware.

In some alternative implementations of an illustrative embodiment, the function or functions noted in the blocks may occur out of the order noted in the figures. For example, in some cases, two blocks shown in succession may be executed substantially concurrently, or the blocks may sometimes be performed in the reverse order, depending upon the functionality involved. Also, other blocks may be added in addition to the illustrated blocks in a flowchart or block diagram.

Turning now to FIG. **13**, an illustration of a block diagram of a data processing system is depicted in accordance with an illustrative embodiment. Data processing system **1300** may be used to implement computer system **146** in FIG. **1**. In this illustrative example, data processing system **1300** includes communications framework **1302**, which provides communications between processor unit **1304**, memory **1306**, persistent storage **1308**, communications unit **1310**, input/output (I/O) unit **1312**, and display **1314**. In this example, communication framework may take the form of a bus system.

Processor unit **1304** serves to execute instructions for software that may be loaded into memory **1306**. Processor unit **1304** may be a number of processors, a multi-processor core, or some other type of processor, depending on the particular implementation.

Memory **1306** and persistent storage **1308** are examples of storage devices **1316**. A storage device is any piece of hardware that is capable of storing information, such as, for example, without limitation, data, program code in functional form, and/or other suitable information either on a temporary basis and/or a permanent basis. Storage devices **1316** may also be referred to as computer readable storage devices in these illustrative examples. Memory **1306**, in these examples, may be, for example, a random access memory or any other suitable volatile or non-volatile storage device. Persistent storage **1308** may take various forms, depending on the particular implementation.

For example, persistent storage **1308** may contain one or more components or devices. For example, persistent storage **1308** may be a hard drive, a flash memory, a rewritable optical disk, a rewritable magnetic tape, or some combination of the above. The media used by persistent storage **1308** also may be removable. For example, a removable hard drive may be used for persistent storage **1308**.

Communications unit **1310**, in these illustrative examples, provides for communications with other data processing systems or devices. In these illustrative examples, communications unit **1310** is a network interface card.

Input/output unit **1312** allows for input and output of data with other devices that may be connected to data processing system **1300**. For example, input/output unit **1312** may provide a connection for user input through a keyboard, a mouse, and/or some other suitable input device. Further, input/output unit **1312** may send output to a printer. Display **1314** provides a mechanism to display information to a user.

Instructions for the operating system, applications, and/or programs may be located in storage devices **1316**, which are in communication with processor unit **1304** through communications framework **1302**. The processes of the different embodiments may be performed by processor unit **1304** using computer-implemented instructions, which may be located in a memory, such as memory **1306**.

These instructions are referred to as program code, computer usable program code, or computer readable program code that may be read and executed by a processor in processor unit **1304**. The program code in the different embodiments may be embodied on different physical or computer readable storage media, such as memory **1306** or persistent storage **1308**.

Program code **1318** is located in a functional form on computer readable media **1320** that is selectively removable and may be loaded onto or transferred to data processing system **1300** for execution by processor unit **1304**. Program code **1318** and computer readable media **1320** form computer program product **1322** in these illustrative examples. In one example, computer readable media **1320** may be computer readable storage media **1324** or computer readable signal media **1326**.

In these illustrative examples, computer readable storage media **1324** is a physical or tangible storage device used to store program code **1318** rather than a medium that propagates or transmits program code **1318**.

Alternatively, program code **1318** may be transferred to data processing system **1300** using computer readable signal media **1326**. Computer readable signal media **1326** may be, for example, a propagated data signal containing program code **1318**. For example, computer readable signal media **1326** may be an electromagnetic signal, an optical signal, and/or any other suitable type of signal. These signals may be transmitted over communications links, such as wireless communications links, optical fiber cable, coaxial cable, a wire, and/or any other suitable type of communications link.

The different components illustrated for data processing system **1300** are not meant to provide architectural limitations to the manner in which different embodiments may be implemented. The different illustrative embodiments may be implemented in a data processing system including components in addition to and/or in place of those illustrated for data processing system **1300**. Other components shown in FIG. **13** can be varied from the illustrative examples shown. The different embodiments may be implemented using any hardware device or system capable of running program code **1318**.

Illustrative embodiments of the disclosure may be described in the context of aircraft manufacturing and service method **1400** as shown in FIG. **14** and aircraft **1500** as shown in FIG. **15**. Motors in electric motor system **102** may be manufactured during various stages of manufacturing and service method **1400**. Additionally, electric motor **104** may be used in manufacturing equipment. In still other examples, controller **108** may be integrated electric motor **104** during maintenance or rework of electric motor **104**.

Turning first to FIG. **14**, an illustration of a block diagram of an aircraft manufacturing and service method is depicted in accordance with an illustrative embodiment. During pre-production, aircraft manufacturing and service method **1400** may include specification and design **1402** of aircraft **1500** in FIG. **15** and material procurement **1404**.

During production, component and subassembly manufacturing **1406** and system integration **1408** of aircraft **1500** in FIG. **15** takes place. Thereafter, aircraft **1500** in FIG. **15** may go through certification and delivery **1410** in order to be placed in service **1412**. While in service **1412** by a customer, aircraft **1500** in FIG. **15** is scheduled for routine maintenance and service **1414**, which may include modification, reconfiguration, refurbishment, and other maintenance or service.

Each of the processes of aircraft manufacturing and service method **1400** may be performed or carried out by a system integrator, a third party, and/or an operator. In these examples, the operator may be a customer. For the purposes of this description, a system integrator may include, without limitation, any number of aircraft manufacturers and major-system subcontractors; a third party may include, without limitation, any number of vendors, subcontractors, and suppliers; and an operator may be an airline, a leasing company, a military entity, a service organization, and so on.

With reference now to FIG. **15**, an illustration of a block diagram of an aircraft is depicted in which an illustrative embodiment may be implemented. In this example, aircraft **1500** is produced by aircraft manufacturing and service method **1400** in FIG. **14** and may include airframe **1502** with plurality of systems **1504** and interior **1506**. Examples of systems **1504** include one or more of propulsion system **1508**, electrical system **1510**, hydraulic system **1512**, and environmental system **1514**. Any number of other systems may be included. Although an aerospace example is shown, different illustrative embodiments may be applied to other industries, such as the automotive industry.

Apparatuses and methods embodied herein may be employed during at least one of the stages of aircraft manufacturing and service method **1400** in FIG. **14**. In one illustrative example, components or subassemblies produced in component and subassembly manufacturing **1406** in FIG. **14** may be fabricated or manufactured in a manner similar to components or subassemblies produced while aircraft **1500** is in service **1412** in FIG. **14**. As yet another example, one or more apparatus embodiments, method embodiments, or a combination thereof may be utilized during production stages, such as component and subassembly manufacturing **1406** and system integration **1408** in FIG. **14**. One or more

apparatus embodiments, method embodiments, or a combination thereof may be utilized while aircraft **1500** is in service **1412** and/or during maintenance and service **1414** in FIG. **14**. The use of a number of the different illustrative embodiments may substantially expedite the assembly of and/or reduce the cost of aircraft **1500**.

Thus, the illustrative embodiments provide a method and apparatus for controlling the operation of an electric motor. In one illustrative example, a controller is configured to identify a start time for a signal based on a back electromotive force present in the electric motor during operation of the electric motor. The start time is for a position of a rotor relative to a group of coils. The controller is further configured to send the signal to the group of coils for the start time identified such that an effect of the back electromotive force on the signal is reduced.

With the use of an illustrative embodiment, the phase advance of an electric motor may be adjusted automatically using a control law in a controller. The illustrative embodiments provide a closed-loop system that may dynamically adjust the phase advance depending on factors specific to each electric motor. Moreover, the use of models and approximations for commutating an electric motor may be substantially reduced or eliminated.

By choosing a phase advance value based upon speed and load, the maximum torque-speed curve for an electric motor can be realized. As a result, electric motors may run at higher speeds and loads than some currently used systems. Additionally, using phase advance at low speeds may allow the electric motor to run more smoothly, thus increasing the reliability of the electric motor.

Illustrative embodiments also provide a method for identifying abnormalities in a waveform profile for different current conditions. Areas may be used to determine where current peaks occur, thereby generating a waveform profile for use by the controller to dynamically change the operating conditions of electric motor **104** in FIG. **1**. A comparison of the areas under a curve representing a particular waveform also may be used to monitor the health of one or more electric motors in an electric motor system. In this manner, the illustrative embodiments increase the operating capabilities of an electric motor system.

The description of the different illustrative embodiments has been presented for purposes of illustration and description, and is not intended to be exhaustive or limited to the embodiments in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art. Further, different illustrative embodiments may provide different features as compared to other illustrative embodiments. The embodiment or embodiments selected are chosen and described in order to best explain the principles of the embodiments, the practical application, and to enable others of ordinary skill in the art to understand the disclosure for various embodiments with various modifications as are suited to the particular use contemplated.

What is claimed is:

1. An apparatus comprising:

a controller configured to

identify a start time for a signal based on a back electromotive force present in an electric motor during operation of the electric motor, wherein the start time is for a position of a rotor relative to a group of coils; and

send the signal to the group of coils using the start time identified, wherein an effect of the back electromotive force on the signal is reduced;

wherein the signal is a current in the electric motor and has a waveform and the controller is configured to

identify a first area under the waveform,

identify a second area under a commanded waveform resulting from a commanded current for the electric motor, and

change the start time based on a difference between the first area and the second area; and

wherein the controller is configured to advance the start time to an earlier start time if the first area is less than the second area by a selected amount.

2. The apparatus of claim **1**, wherein the current has a number of characteristics based on the start time and the back electromotive force in the electric motor.

3. The apparatus of claim **2**, wherein the waveform for the current has a desired amplitude over a period of time based on a selection of the start time.

4. The apparatus of claim **3**, wherein the desired amplitude is substantially equal to a commanded amplitude for the current over the period of time.

5. The apparatus of claim **1** further comprising:

a sensor system configured to generate information about the back electromotive force and send the information to the controller.

6. The apparatus of claim **5**, wherein the sensor system is configured to measure the current in the group of coils to generate the information about the back electromotive force.

7. The apparatus of claim **1**, wherein the controller is configured to change the start time based on a change in the back electromotive force.

8. The apparatus of claim **1**, wherein the controller is configured to divide the waveform into segments and identify an area under the segments to identify the first area.

9. The apparatus of claim **1**, wherein the electric motor is selected from one of a brushless direct current electric motor, a reluctance motor, a variable reluctance motor, and a virtual ellipse device.

10. An electric motor system comprising:

an electric motor having a rotor and a group of coils;

a sensor system configured to generate information about a back electromotive force in the electric motor during operation of the electric motor; and

a controller configured to

receive the information from the sensor system;

identify a start time for a current based on the back electromotive force present in the electric motor during operation of the electric motor using the information from the sensor system, wherein the start time is for a position of the rotor relative to the group of coils; and

send the current to the group of coils using the start time identified, wherein an effect of the back electromotive force on a signal is reduced;

wherein the current in the electric motor has a waveform and the controller is configured to

identify a first area under the waveform,

identify a second area under a commanded waveform resulting from a commanded current for the electric motor, and

change the start time based on a difference between the first area and the second area.

11. A method for controlling an electric motor, the method comprising:

identifying a start time for a signal based on a back electromotive force present in the electric motor during operation of the electric motor, wherein the start time is for a position of a rotor relative to a group of coils in the

electric motor, and wherein the signal is a current in the electric motor and has a waveform;

identifying a first area under the waveform;

identifying a second area under a commanded waveform resulting from a commanded current for the electric motor;

changing the start time based on a difference between the first area and the second area; and

sending the signal to the group of coils using the start time identified, wherein an effect of the back electromotive force on the signal is reduced.

12. The method of claim **11**, wherein a waveform for a current has a desired amplitude over a period of time based on a selection of the start time.

13. The method of claim **12**, wherein the desired amplitude is substantially equal to a commanded amplitude for the current over the period of time.

14. The method of claim **11** further comprising:

receiving information about the back electromotive force, wherein the information is a measurement of a current of the group of coils to generate the information about the back electromotive force.

15. The method of claim **11** further comprising:

changing the start time based on a change in the back electromotive force.

16. The method of claim **11**, wherein the changing step comprises:

advancing the start time to an earlier start time if the first area is less than the second area by a selected amount.

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